A SIMPLIFIED MODEL FOR PREDICTING THERMAL LOSSES IN DUCT-WORK SYSTEMS

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ABSTRACT

Air is usually the final method for thermal distribution in a building. The air distribution system (duct-work) may be located at several places inside or outside the building. The location of the ducts leads to thermal losses. These losses consist of: leakage, conduction, and thermal cycling. Traditionally, quantifying these loses requires temperature and flow data from many places in the system.

This paper presents a model for quantifying these losses requiring less input data. The model breaks the delivery efficiency down into supply and return effectiveness terms, each of which may be further broken down into individual sections. This allows pinpoint identification of sections of the duct system contributing to poor performance. The inputs to the model are the physical properties of the ducts, the cold deck (supply plenum), room, and ambient temperatures, and the amount the system leaks (as a fraction of the total flow). The physical properties are combined into a conduction efficiency term. The temperatures are combined into a conduction potential term.

INTRODUCTION

A typical building uses air as the final means of thermal distribution. Air distribution takes place with a variety of air handling equipment usually attached to some form of duct-work. The duct-work system itself is subjected to a variety of thermal loss mechanisms. Figure 1 shows a roof-mounted application and the potential losses. The major loss mechanisms are-

- Air leakage
- Conduction losses
- Thermal cycling

Air leakage prevents the desired amount of air from reaching the conditioned space. Depending on the location of the leak, the leak may or may not constitute an entire thermal-loss, with the duct-work located outside the building (e.g., located on the roof) the leak is a total loss. However, with supply ducts located in a ceiling mounted return-air cavity, the losses simply act as a short-circuit. Even if the energy is not "lost," the leak, in the case of a variable air volume (VAV) system, artificially raises the static pressure requirements of the system causing excessive fan power use, with a constant air volume (CAV) system the leak leads to lower than necessary cold deck temperatures (or simply warmer rooms).

Leakage is a function of the quality of construction, and the construction techniques. Most leaks occur at joints and connections. How these connections were made and sealed determine how much the system leaks right after installation, as well as several years later. Researchers found out that leakage rates between 15% and 30+% of the system fan flow are common in small commercial buildings (Delp et al. 1997, Cummings et al. 1996).

Conduction losses raise the temperature of the air as it moves through the duct. This temperature rise reduces the effective capacity of the system. Conduction losses depend on the physical properties of the duct as well as its location. For a heavily insulated duct, or one located in a return air plenum, conduction losses are negligible. With the ducts located in un-conditioned spaces, or if the system operates with a high cold-deck temperature, conduction losses can exceed 50% of the system's potential capacity.

Thermal cycling losses occur as a result of transients in system operation. They are due to changing the temperature of the duct system itself. This paper deals primarily with chilled water systems. These systems usually operate in semi-steady state modes, as a result thermal cycling is not considered here.

This paper presents a simplified steady-state model for evaluating thermal losses in duct-work systems. It discusses the important parameters for identifying sections of the duct-work system that would benefit from a retrofit, and illustrates these parameters with two different VAV duct sections: insulated and un-insulated.

DISCUSSION

Delivery efficiency as it applies to the thermal distribution system, in this case the duct-work, is the ratio of the energy delivered by the duct system to that supplied to the duct system eq(1).

$$h_{del} \equiv \frac{\textit{Energy delivered by the duct system}}{\textit{Energy supplied to the duct system}} = \frac{\dot{m}_{reg}(T_{reg} - T_{room})}{\dot{m}_{fan}(T_{supply\ plenum} - T_{return\ plenum})} \qquad (1)$$

This is the ultimate check of the distribution system. However, since it combines all of the losses, supply and return side, into a single number it only tells how good or bad the entire system is. Our goal is to identify sections of the duct system that need work. This is achieved by introducing effectiveness terms allowing investigation of individual sections of the duct system. Before discussion of effectiveness, modeling the performance of the duct system requires physical properties of the ducts, these form the conduction efficiency, and the temperatures in and around the duct, which define the conduction potential.

Conduction efficiency

Conduction efficiency relates the temperature change of an air stream flowing through a duct section to the physical properties of that duct section. Figure 2 shows a duct section and the nomenclature as it applies to conduction efficiency. The ratio of the temperature difference, inside to outside, at the exit of the duct section to the same difference at the beginning of the duct section defines the conduction efficiency. Solution of an ordinary differential equation, the heat exchanger equation, yields eq. (2) (Holman 1981).

$$b \equiv \frac{(T_{out\ of\ the\ duct} - T_{\infty})}{(T_{into\ the\ duct} - T_{\infty})} = \exp\left(-\frac{PL}{mC_pR}\right) \qquad (2)$$

where

P:	The perimeter of the duct
L:	Length of the duct
m:	The mass flow rate of air through the duct
C_p:	The specific heat of air
R:	The thermal resistance of the duct
$T_{¥}$:	Temperature of the ambient surroundings around the duct
$T_{out\ of\ the\ duct}$:	Temperature of the air leaving the duct section
$T_{into\ the\ duct}$:	Temperature of the air entering into the duct section

In IP units this becomes

$$b = \exp\left(-\frac{p\,d\ /\ 12\ L}{1.1 cfm\ R}\right) \qquad (3)$$

where

d:	Duct diameter (in.)
L:	Length of the duct (ft.)
cfm:	Flow through the duct (cfm)
R:	R-value of duct ($ft^2\ {}^{O}F/BTU$)

In a perfectly insulated duct the temperature does not change, and the conduction efficiency is one. The other extreme is where the exit temperature is the same as the ambient surroundings, yielding a conduction efficiency of zero. Conduction efficiency is strictly a function of the physical properties of the duct and the air flow rate through the duct. It does not depend on the ambient conditions. Figure 2 shows the conduction efficiency of two pieces of duct with varying air flow rates. The only difference in the ducts is in the insulation, the one has none and the other has the typical 1” nominal thickness.

Conduction Potential

Conduction losses are proportional to the temperature difference between supply air and ambient surroundings, while system capacity is proportional to the difference in supply air and the room temperature. Thus, conduction losses and system capacity follow different scaling parameters. The conduction potential combines these parameters in a single term eq.(4).

$$\frac{\Delta T}{\Delta T_p} = \frac{(T_{supply\ plenum} - T_{\infty})}{(T_{supply\ plenum} - T_{room})} \tag{4}$$

Conduction potential is strictly a function of these temperatures, with no dependence on the physical properties of the duct. Increasing either the supply plenum or ambient surrounding temperatures causes an increase in conduction losses as a fraction of system capacity. An increase in either of these temperatures increases the conduction potential; the potential for conduction loss expressed as a fraction of the system capacity. The temperature for the ambient surroundings should be the effective temperature around the duct. For example, with a horizontal duct exposed to sun-light on a roof, the ambient temperature is approximated by the sol-air temperature. Delp et al. measured just such ducts with surface temperatures of ~170^{o}F, leading to conduction potentials as high as 12 (Delp et al. 1996).

Figure 3 shows the conduction potential over a range of ambient temperatures using several different cold deck (supply plenum) temperatures. Figure 4 shows how the delivery efficiency varies with the conduction potential using an insulated and un-insulated duct, both without any leakage.

Supply Effectiveness

Supply effectiveness, eq.(5), is a measure of the fraction of capacity lost by the supply system. It is the ratio of the capacity supplied by the ductwork to the space, to the potential capacity put into the supply at the plenum.

$$e_s \equiv \frac{Delivered\ Capacity}{Potential\ Capacity} = \frac{\dot{m}_{reg}(T_{reg} - T_{room})}{\dot{m}_{fan}(T_{supply\ plenum} - T_{room})} \tag{5}$$

The formulation in eq(5) requires knowing the temperature at the end of the duct, something that is not usually known. The following simplified model, which uses conduction efficiency and potential terms, developed by Delp et al. (Delp et al. 1996) predicts supply effectiveness eq(6).

$$e_s = a_s - a_s(1 - b_s)\frac{\Delta T}{\Delta T_p} \tag{6}$$

where

a: Fraction of air making it to the supply registers.

The subscript *s* denotes supply side. The quanity(1-α) represents the leakage as a fraction of the system flow. The model assumes this leakage occurs at the end of the duct.

Figure 6 shows supply effectiveness over a range of flow rates through the insulated and un-insulated ducts. The conditions while rather severe, a conduction potential of 2.78, are not un-realistic.

Return Effectiveness

A similar approach works for the return system. Return losses in a cooling system tend to raise the temperature of the air; therefore, the return effectiveness is the ratio of the minimum energy to the actual energy required to condition the space. The minimum energy is the temperature difference between the supply plenum and the room; the actual energy is the difference between the supply and return plenums. Eq(7) defines return effectiveness.

$$e_r \equiv \frac{Minimum\ Energy}{Actual\ Energy} = \frac{(T_{supply\ plenum} - T_{room})}{(T_{supply\ plenum} - T_{return\ plenum})} \tag{7}$$

A return duct which in which the temperature does not change has an effectiveness of one. It is possible for the return effectiveness to be greater than one if the "losses" lower the temperature between the room and return plenum. This occurs when the ambient surroundings of the duct are lower than the room temperature.

Using the conduction efficiency and potential terms defined in eqs(2) and (4), eq(8) provides a model for return effectiveness.

$$e_r = \frac{1}{\frac{\Delta T}{\Delta T_p} - a_r b_r\left(\frac{\Delta T}{\Delta T_p} - 1\right)} \tag{8}$$

a: Fraction of air at the return plenum coming from the supply registers

The subscript *r* denotes return side. On the return side, the model assumes the leaks occur at the beginning, room side, of the return section.

Figure 7 shows return effectiveness over a range of flow rates through the insulated and un-insulated ducts using the same conduction potential of 2.78.

Delivery Efficiency

The potential capacity put into the supply at the plenum is the same as minimum energy required to condition the space. This allows combing the two effectiveness' yielding the distribution delivery efficiency. As defined above, this efficiency is the ratio of the energy delivered by the duct system to that supplied to the duct system.

$$h_{del} = e_s \cdot e_r \tag{9}$$

Figure 8 combines the previous examples in figures 6 and 7, and shows delivery efficiency over a range of flow rates through the insulated and un-insulated ducts using the same conduction potential of 2.78.

Extended Model

The model is easily extended by further breaking the duct into individual sections. The delivered capacity, from an individual duct section, in eq(5) is the same as the potential capacity for the next downstream duct section. Thus, the supply effectiveness is the product of the individual supply effectiveness' eq(10).

$$e_s = \prod_i e_{s,i} \tag{10}$$

where

$$e_{s,i} = a_{s,i} - a_{s,i}(1 - b_{s,i})\frac{\Delta T}{\Delta T_{p,i}} \tag{11}$$

where

$a_{s,i}$: Fraction of air making it to the following duct section.

and
$$b_{s,i} \equiv \frac{(T_{out\ of\ the\ duct\ section} - T_\infty)}{(T_{into\ the\ duct\ section} - T_\infty)} = \exp\left(-\frac{PL}{mC_pR}\right) \tag{12}$$

and
$$\frac{\Delta T}{\Delta T_{p,i}} = \frac{(T_{into\ the\ duct\ section} - T_\infty)}{(T_{into\ the\ duct\ section} - T_{room})} \tag{13}$$

This allows pinpoint identification of individual sections of the duct system responsible for poor performance. The same approach also applies to return effectiveness.

CONCLUSIONS

Effectiveness calculations provide a framework for evaluating a duct system. They allow identification of sections of the system contributing to poor performance. Conduction potential illustrates the importance of identifying the proper ambient temperature for any given duct section, along with the impact of raising the cold-deck temperature. The conduction efficiency term has little significance on its own, but is required in effectiveness calculations.

FIGURES

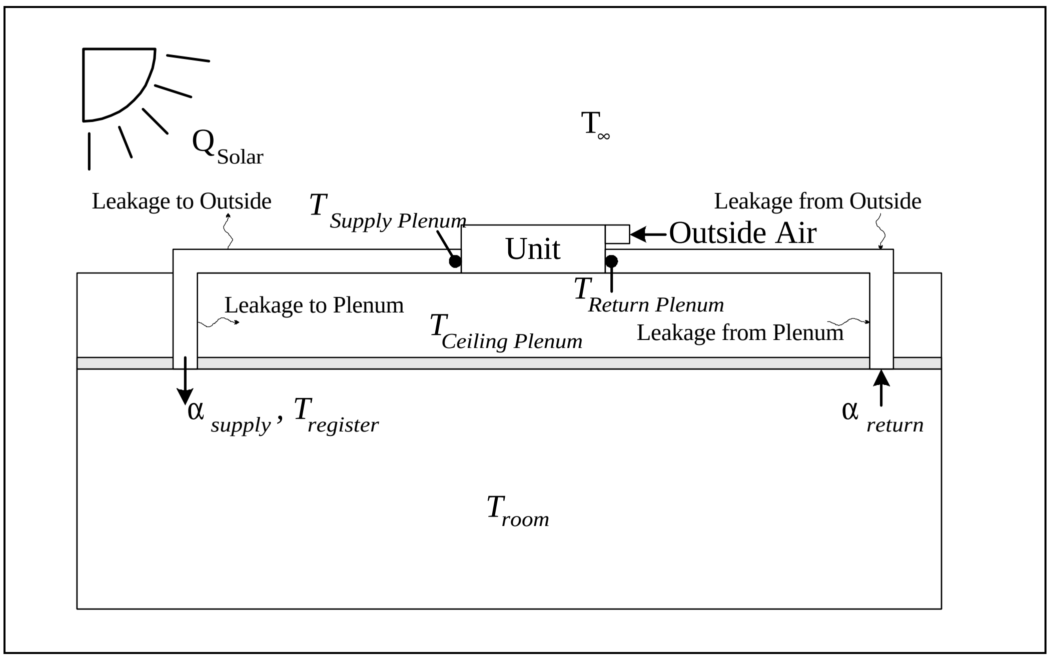

Figure 1. Layout of a typical roof-top mounted HVAC unit. The nomenclature for effectiveness calculations. Source: LBNL.

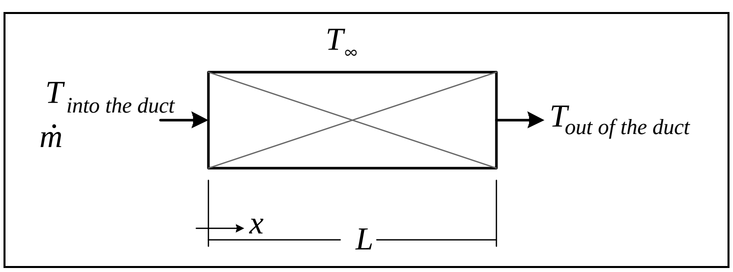

Figure 2. Ductwork as a heat-exchanger. The nomenclature for heat-exchanger calculations as they apply to a piece of ductwork. Source: LBNL.

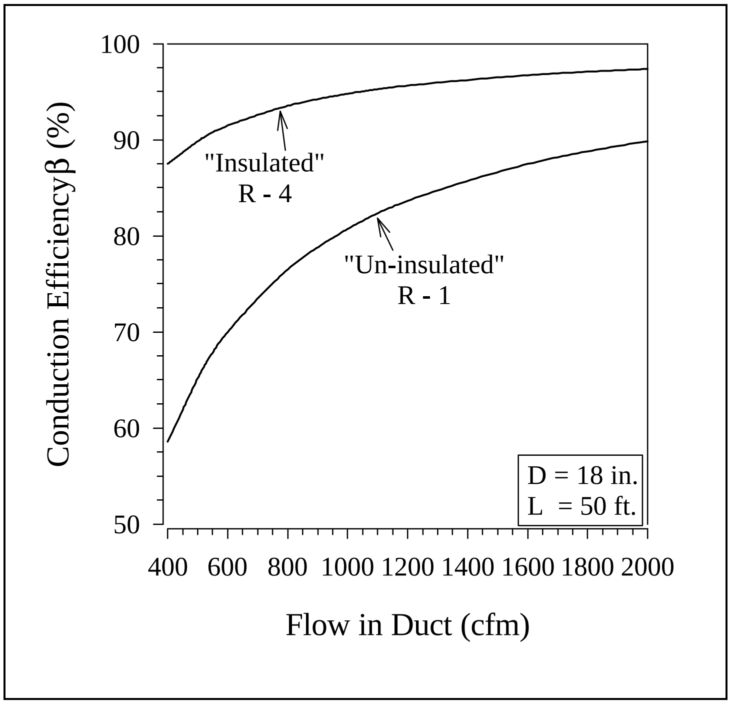

Figure 3. Conduction Efficiency versus Flow in Duct. For a single size duct, un-insulated and 1” nominally insulated. Source: LBNL.

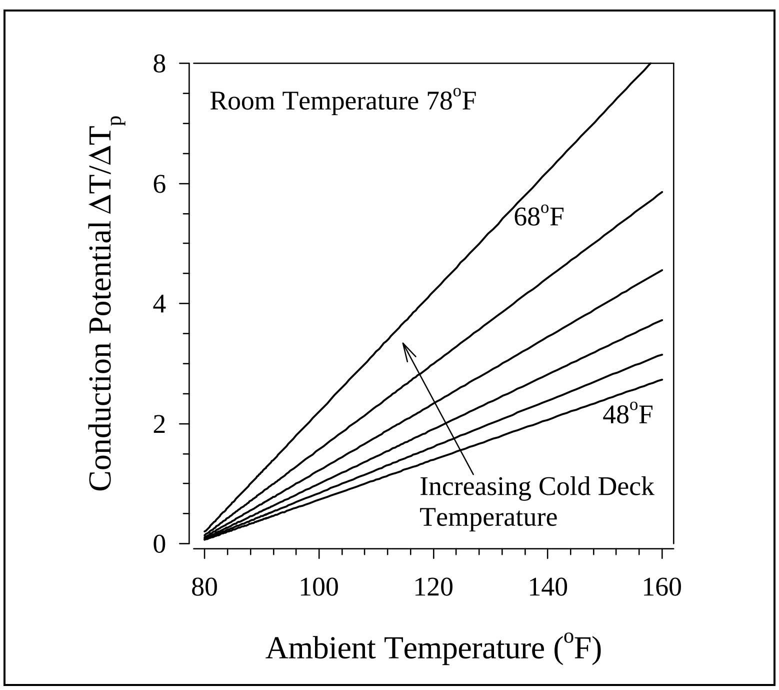

Figure 4. Conduction Potential versus Ambient Temperature. Assumes a fixed room temperature, and several cold deck (supply plenum) temperatures. Source: LBNL.

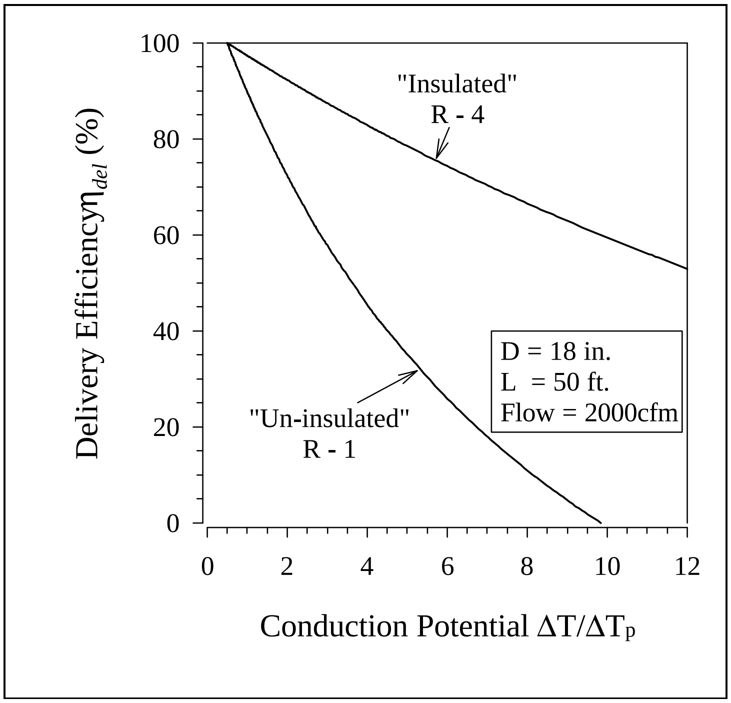

Figure 5. Delivery efficiency versus Conduction Potential. Delivery efficiency using an equal length (L) and size (D) supply and return system. Both supply and return assume zero leakage. Source: LBNL.

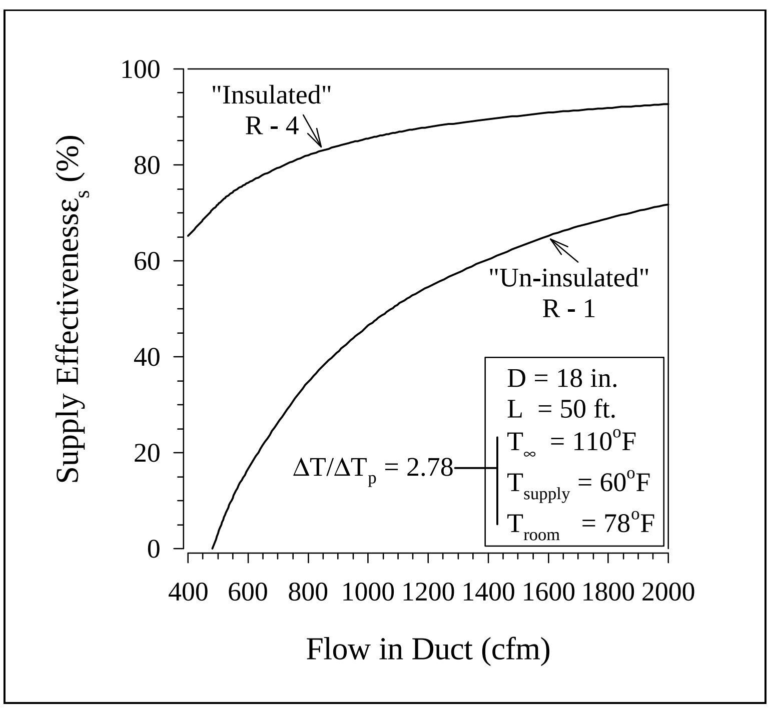

Figure 6. Supply Effectiveness versus Flow in the duct. Zero leakage case. Source: LBNL.

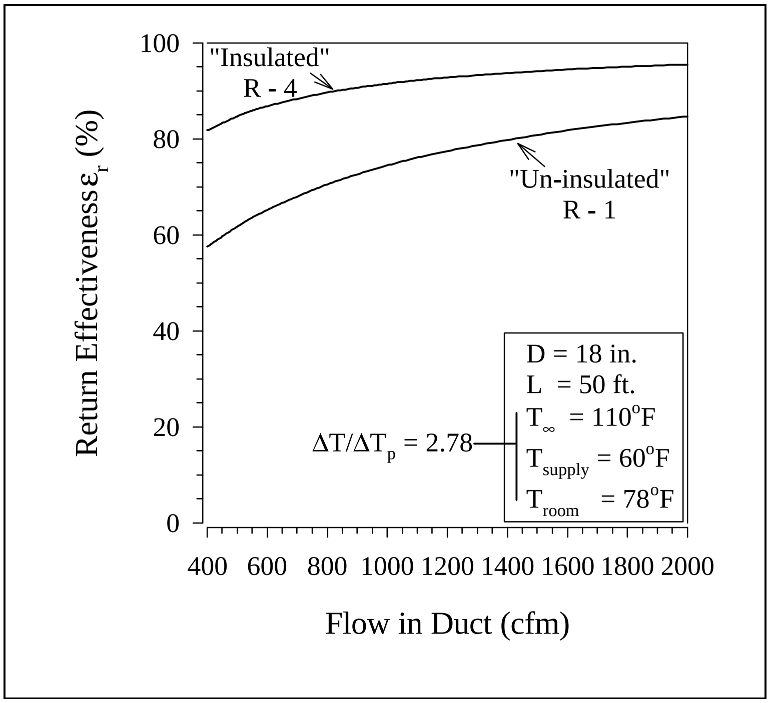

Figure 7. Return Effectiveness versus Flow in the duct. Zero leakage case. Source: LBNL.

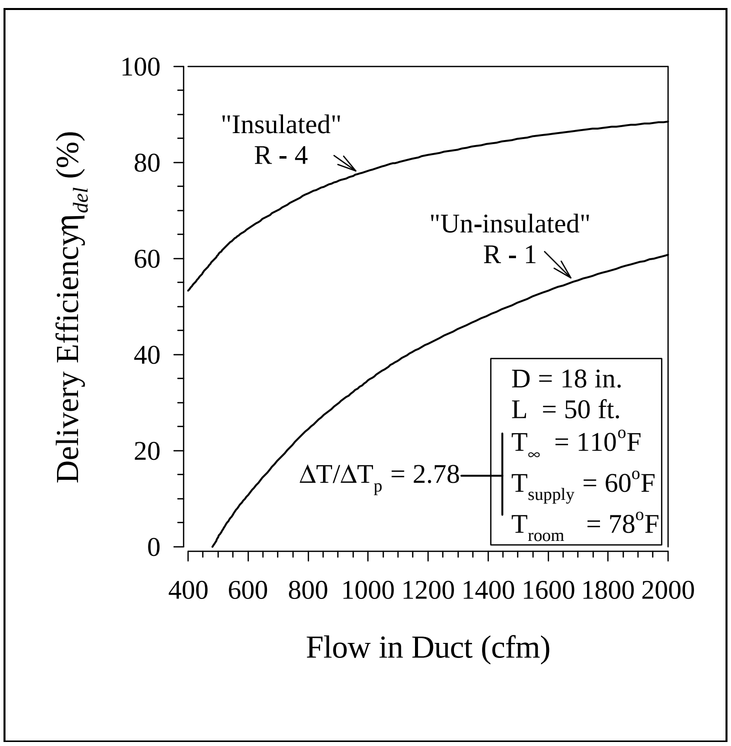

Figure 8. Delivery Efficiency versus Flow in the duct. Zero leakage case. Source: LBNL.

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